Observations of EUV spectra from highly charged heavy ions in optically thin plasmas for benchmarking models

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Outline

- Heavy ions applicable to BEUV light sources
  - For lithography & biological microscopy
- EUV spectroscopy in optically thin plasmas
  - LHD — a magnetically confined fusion device
  - Benefits for benchmarking models
- EUV spectra of lanthanides (e.g., Gd)
  - Temperature dependence
  - Identifications & interpretations
- Z dependence of EUV spectra
  - Comparisons with LPPs and calculations
Beyond EUV sources using lanthanides?

**Trend of LSI feature size**

- **MLM near 6.X nm**
  - 200 period ML's
  - Reflectance vs. Wavelength (nm)
  - Gd plasma & Mo/Si @ 13.5 nm
  - ArF laser @ 193 nm
  - Present day @ ? nm

**UTA features of gadolinium near 6.X nm**

- Vacuum spark
- Laser plasma
- UTA features of gadolinium near 6.7–6.8 nm
- Sn plasma & Mo/Si @ 13.5 nm

**UTA (Unresolved Transition Array)**


Biological microscopy in water window & carbon window

Transparencies of biological materials

Water Window

Carbon Window

Oxygen K-edge

Carbon K-edge

Sample image in carbon window

(bush-cricket wing)

4.5 nm

visible


Proposed optics for soft X-ray microscopy

Schwarzchild Optics

Biological sample

EUV

Laser

Soft X-ray CCD

Pinhole

Multilayer mirror

Plasma light source


LPP of Au, Pb, Bi, ... ?

EUV spectra of tin in optically thick/thin plasmas

- Higher opacity and small scale length in LPP
  - Sometimes more difficult to benchmark with models


Why experiment in magnetically confined fusion (MCF) device?

- Simple spectrum without large absorption/broadening
- Controllable $T_e$ and $n_e$ in wide ranges
- Direct/precise measurements of $T_e$ and $n_e$ without modeling

Suitable for benchmarking models
Large-scale facility for MCF at the National Institute for Fusion Science (NIFS)
High temperature (keV order) and low density \( n_e = 10^{18}\text{~to~}10^{20} \text{ m}^{-3} \) plasmas are routinely produced in large volume (30 m\(^3\)).
Tracer encapsulated solid pellet (TESPEL) injection system is available.
Highly charged heavy ions can be easily generated in optically thin conditions.
Ion stages mainly observed in LHD

Contribution of open N shell (n=4) ions are commonly important in these high Z elements
# General spectral feature of open N shell ions

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<thead>
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<th># of Electrons</th>
<th>Isotopic sequence</th>
<th>Ground State Configuration</th>
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<td>Eu</td>
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</table>

- **Open 4s/4p ions**
- **Open (partially filled) 4d ions** \([4p^64d^k]\)
- **Open (partially filled) 4f ions** \([4d^{10}4f^k]\)
- **Smaller number of energy levels in subshells**
- **Discrete line spectral feature**
- **Larger number of energy levels in subshells**
- **Quasicontinuum UTA feature**
- **Huge number of energy levels**
- **More complex UTA feature**
LHD discharge with Gd (Z=64) pellet injection

![Graph showing plasma behavior with Gd pellet injection at different times (4.5 s, 5.1 s, 5.9 s).](image)

- **4.5 s**
- **5.1 s**
- **5.9 s**

**Time (s)**

- **Gd pellet injection**
Different EUV spectra from Gd ions in LHD

\[ T_{\text{max}} = 2.2 \text{ keV} \]

\[ T_{\text{max}} = 1.0 \text{ keV} \]

\[ T_{\text{max}} = 0.24 \text{ keV} \]

# Calculation of unknown lines by Hullac and Grasp code

<table>
<thead>
<tr>
<th>Measured wavelength (nm)</th>
<th>Calculated wavelength (nm)</th>
<th>Ion</th>
<th>Transition</th>
<th>Previous works</th>
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<tr>
<td>7.279</td>
<td>7.268 (H) 7.168 (G)</td>
<td>Gd XXXIII (Ge-like)</td>
<td>$4s^24p^2_2 - 4s^24p4d_1$</td>
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<tr>
<td>7.279 (H) 7.288 (G)</td>
<td>Gd XXXIV (Ga-like)</td>
<td>$4s^24p_{1/2} - 4s^24d_{3/2}$</td>
<td>7.41 (Exp.) [1] 7.326 (Theory)</td>
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<td>7.409</td>
<td>7.406 (H) 7.411 (G)</td>
<td>Gd XXXV (Zn-like)</td>
<td>$4s4p_{1/2} - 4s4d_{2}$</td>
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<td>7.524</td>
<td>7.522 (H) 7.528 (G)</td>
<td>Gd XXXVI (Cu-like)</td>
<td>$4p_{1/2} - 4d_{3/2}$</td>
<td>7.5259 (Exp.) [2]</td>
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<tr>
<td>7.583</td>
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</tr>
</tbody>
</table>

H: Calculated by Hullac  
G: Calculated by Grasp  
exp. in TEXT tokamak  
exp. in LPP
Comparison of UTA features with calculations.

Spectral bands of Gd ions
(by Cowan's code with CI)

Synthesized spectra of Gd ions
(by Grasp code with CI)

Construction of collisional-radiative modeling should be necessary for detailed analyses.
Z dependence of the lanthanides spectral appearance in LHD

Nd (Z=60)
Pm (Z=61)
Sm (Z=62)
Eu (Z=63)
Gd (Z=64)
Tb (Z=65)
Dy (Z=66)
Ho (Z=67)
Er (Z=68)
Tm (Z=69)
Yb (Z=70)

Not yet measured
Not yet measured
Coming soon
Not yet measured
Not yet measured
Not yet measured
Coming soon
Not yet measured
Not yet measured
Coming soon

High $T_e$
Cu-like

Low (hollow) $T_e$
Ag-like
Z dependence of Au–Bi in LPP and LHD

Comparisons with FAC code calculation

Comparisons with FAC code calculation (contd.)

- The UTAs from open 4f ions observed in LPP are missing in LHD.
- The spectra of 4p-4d transitions are weak or missing in LHD and LPP.


FAC code calculation for 4d ions

Difference in excitation process?
Summary

- EUV spectroscopy in optically thin plasmas such as LHD is a good experimental platform for benchmarking models of highly charged heavy ions relevant to the applications to EUV lithography and biological microscopy.

- We have measured discrete and narrowed UTA features of EUV spectra from lanthanide ions in LHD plasmas following the change in electron temperature.

- We have also observed Z dependence of EUV spectra from lanthanides to bismuth ions, and comparative analyses with LPPs and theoretical models have got started.